Seeing All the Excitons

New Insights in the Metal-Insulator Transition

A long-standing problem of condensed matter physics is to understand metal-insulator transitions; transformations of a material between phases that conduct electrical current (metal) and those that do not (insulator). A prototypical case is the "Mott transition" between a metallic electron-hole (*e-h*) plasma and an exciton gas and an in semiconductors. An MSD group, under the direction of Daniel Chemla, has developed new spectroscopic techniques to elucidate these phenomena.

In semiconductors, when photons of energy close to the fundamental band gap E_g are absorbed, they generate *e-h* pairs. At energies significantly above E_g, the electrons and holes move largely independent of each other and form a conducting gas of unbound *e-h* pairs. However, electrons and holes always interact via the Coulomb force and - due to their opposite charge - can form bound states called "excitons". Due to the attractive binding, excitons exhibit a narrow resonance at an energy slightly below the band gap. Since excitons are akin to the neutral hydrogen atom, they are insulating, and their formation from unbound *e-h* pairs corresponds to a metal – insulator transition (and vice versa). Although the properties of excitons have been intensively studied for over 50 years, many aspects of the excitonic Mott transition remain elusive. Most techniques employed so far to study the dynamics – e.g. near band gap absorption or photoluminescence – are limited by the small photon momentum and thus sense only the subset of *e-h* pairs with vanishing center-of-mass momenta. Metal-insulator transitions – in contrast – involve charge pairs in a profoundly larger momentum range.

A major experimental difficulty in studying excitons stems from the vastly different energy scales involved. Creation or destruction of unbound *e-h* pairs and excitons demands photons in the visible or near-infrared with electron-Volt (eV) energies. In contrast, transformations between excitons and unbound pairs, as well as their intrinsic excitations, occur on a comparably minuscule meV energy scale that corresponds to far-infrared, terahertz (THz) frequencies and sub-millimeter wavelengths. Robert Kaindl and Marc Carnahan in Chemla's MSD group developed a new method specifically designed to combine both worlds. Perfectly synchronizing near-infrared and THz pulses, the group was able to follow the picosecond dynamics (1 ps = 10^{-12} sec) of quasi-two dimensional carriers in gallium arsenide quantum wells. Excitons or unbound *e-h* pairs are initially created with shaped near-infrared pulses ($E \approx 1.55$ eV) derived from a Ti:sapphire laser. Terahertz probe pulses, obtained by "optical rectification", strike the carriers with time delay Δt (Fig. 1a) to sample their transient, far-infrared electromagnetic response. The THz pulses yield sensitive snapshots of excitons and *e-h* pairs with *any* center of mass momentum, since they probe the internal degrees of freedom as illustrated in Fig. 1(b). The transient response is described by changes in the real part of the frequency-dependent conductivity $\sigma_1(\omega)$ and the dielectric function $\varepsilon_1(\omega)$, and their simultaneous availability yields important physical insight. Since insulating and conducting phases show a vastly different THz response (Fig. 2), the transformation from one species to another can be tracked precisely. Figure 3(a) reveals the fast ionization of excitons, i.e. the transition from an exciton gas to an unbound *e-h* gas. Conversely, the formation of excitons from initially unbound *e-h* pairs can be comprehensively studied (Fig. 3b). The latter sequences clearly show that the two transition phenomena exhibit spectra in reverse order, although occuring on time scales different by an order of magnitude: as usual it is easier to break up a couple that to form a stable one.

These first observations provide many new insights into metal-insulator transitions. Most unexpected is the occurence of a strong correlation enhancement roughly at the exciton peak in the conducting phase, reminiscent of a "precursor" of the excitons. This enhancement emerges after insulator-metal transformation into conducting, unbound *e-h* pairs (100 ps in Fig. 3a), and even immediately after resonant creation of unbound pairs (1 ps in Fig. 3b). The exact nature of these conducting yet correlated phases is currently unknown.

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